

**A METHOD AND APPARATUS FOR DETERMINING THE
LOCATION OF A UNIT USING NEIGHBOR LISTS**

**STATEMENT REGARDING FEDERALLY
SPONSORED RESEARCH OR DEVELOPMENT**

5

This invention was made with United States Government support under 70NANB2H3001 awarded by the National Institute of Standards and Technology (NIST). The United States Government has certain rights in the invention.

10

FIELD OF THE INVENTION

The present invention relates generally to the location of a unit operating within a network including a plurality of units, and more particularly, to the determination of a location, based upon the detected presence of units, whose locations are known, near the unit to be located and their presence near other units,
15 which are nearby the unit to be located.

BACKGROUND OF THE INVENTION

In densely populated networks, one such example including a warehouse, where it is desirable to track the location of items located in relatively close
20 proximity, a system may include tens of thousands items to be tracked. Still further, in connection with the warehouse example, the large volume of items may be moving into and out of the warehouse with considerable frequency, where some of the units may stay in place for only a few minutes and others may stay in the same place for days or weeks. The large volume of items and the constant shuffling of the items can
25 make it difficult to maintain an accurate fix on any one item's location within the warehouse. The same is true of other environments, where it is desirable to track the current location of large groups of items, which are within relatively close proximity.

Traditional triangulation or other relative location technologies, often generally require an ability to make good ranging measurements. This is especially
30 problematic for a high density environment, like a warehouse, where there are a large number of surfaces off of which a signal can reflect, and/or where the item density

requires a relatively high degree of precision in order to allow for the item to be readily distinguished from the other nearby items.

In absence of a realistic path loss model in an ever changing environment, power-based measurements, such as an indication of received signal strength, may not provide good ranging information. Where ranging is determined using time-based measurements, micro-second range resolution will often only enable a range resolution in the hundreds of meters, while nano-second resolution will often be required to enable a range resolution on the order of approximately one meter. However, generally, there is an inverse relationship between cost and timing resolution, and unfortunately, in environments where large number of items are to be tracked, the higher cost of higher precision timing circuits can be an important factor, and may be impractical if the higher precision timing circuits need to be associated with or incorporated into each of the items to be tracked.

Consequently, it would be beneficial to develop a cost effective method and apparatus for determining a location of a plurality of units. Still further, it would be beneficial to develop systems and methods that produce a sufficiently high location determination precision, which could be used in more crowded environments having higher item density, which largely avoids extensive usage of potentially more costly, solutions involving higher precision ranging measurements.

The present inventors have recognized that the use of neighbor lists, in conjunction with a subset of units who know or are able to determine their location may be a beneficial alternative approach, as opposed to a solution, which makes more comprehensive usage of determined ranging information. The neighbor lists could be used to establish proximity relative to one or more units that are nearby, and whose location are known. By incorporating the use of neighbor lists of nearby units, a relative proximity with respect to the reference units whose location are known may be able to be determined, which in turn can be used to provide a location estimate.

SUMMARY OF THE INVENTION

The present invention provides a method for determining a location of one of a plurality of units, each unit being communicatively coupled to at least some of the other plurality of units, where at least some of the plurality of units are reference
5 units, whose locations are known. The method includes communicating with the units within communication range of the unit to be located, and establishing a neighbor list for the unit to be located and each of a group of associated units, where the associated units are a subset of the plurality of units and include one or more units other than the unit to be located, which are located proximate to the unit to be located. The neighbor
10 list includes the list of the units that are in communication range of the respective associated unit.

Any reference units contained in each of the neighbor lists of the unit to be located and the associated units are then identified, and an aggregate value corresponding to the number of occurrences of each of the reference units in the
15 neighbor list of the unit to be located and the neighbor lists of each of the associated units is determined. The location of the unit to be located is then determined, based upon the known locations of the reference units and the aggregate value of identified occurrences of each of the reference units in the corresponding neighbor lists.

In at least one embodiment, the associated units include the units within
20 communication range of the unit to be located.

In at least a further embodiment, the reference units are substantially stationary, and are proximately spaced at regular intervals.

In a still further embodiment, the reference units are mobile and include provisions for periodically updating the reference units' location information.

25 The present invention further provides a location determination module for use in a system of a plurality of units, wherein at least some of the units are reference units, whose location are known, and each unit is communicatively coupled to at least some of the other units. The location determination module includes a transceiver having a finite communication range, and a processor, coupled to the transceiver. The
30 processor includes a storage area for maintaining a neighbor list including a list of the units within communication range of the transceiver, a discriminator for

distinguishing between reference units and non-reference units contained in one or more neighbor lists, and a calculation element for determining an estimated location. The estimated location is based upon the number of occurrences of each of the reference units in the neighbor list and the neighbor lists of a plurality of associated
5 units, and the known location of the reference units.

These and other features, and advantages of this invention are evident from the following description of one or more preferred embodiments of this invention, with reference to the accompanying drawings.

10 BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a partial spatial overview diagram illustrating an exemplary spatial relationship between nearby members of at least a portion of a communication network, in accordance with at least one embodiment of the present invention;

15 FIG. 2 is a more complete spatial overview diagram of an overview of at least a portion of an exemplary communication network illustrating the spatial relationship between a greater number of nearby members from a portion of the communication network;

FIG. 3 is an example of possible placement of a set of reference units, which can be generally substantially stationary, for use by other nearby units in determining
20 a location within an area, in accordance with at least one aspect of the present invention;

FIG. 4 is at least a further example of possible placement of reference units, which can be substantially stationary, for use in determining a location within an area, in accordance with at least a further aspect of the present invention;

25 FIG. 5 is a flow diagram of a method for determining a location of a unit, in accordance with at least one embodiment of the present invention;

FIG. 6 is a block diagram of a location determination module for use in a unit to be located, in accordance with at least one embodiment of the present invention; and

FIG. 7 is a block diagram of a reference unit for use in determining the location of the unit to be located, in accordance with at least one embodiment of the present invention.

5 **DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT(S)**

While the present invention is susceptible of embodiment in various forms, there is shown in the drawings and will hereinafter be described presently preferred embodiments with the understanding that the present disclosure is to be considered an exemplification of the invention and is not intended to limit the invention to the
10 specific embodiments illustrated.

FIG. 1 illustrates a diagram illustrating an exemplary spatial relationship between nearby members of at least a portion of a communication network 10, including a reference unit 12, illustrated as a triangle, and four blind units, one of which is illustrated as a square and represents a unit 14 to be located. The other three
15 units 16A-C are illustrated as circles, and represent other blind units present in the network. Generally, a reference unit corresponds to a unit, whose location is known, and a blind unit represents one of one or more units for which the unit's location would need to be determined and/or estimated.

Each unit, generally, includes a transceiver and corresponding antenna, which
20 support wireless communication between the other units within communication range. An exemplary communication range 18A-C for each of the blind units including an exemplary communication range 20 for the blind unit 14, which is being located, is illustrated. The communication range is illustrated by a circle having a center which generally corresponds to the respective blind unit. In the illustrated embodiment, the
25 reference unit 12 is shown outside of the communication range of the blind unit to be located 14, but is in communication range of the other three illustrated blind units 16A-C, which are also in communication range with the blind unit to be located 14.

Despite being out of range of one another, in at least some instances, a communication path between the reference unit 12 and the blind unit to be located 14
30 can exist if the communication is relayed via one or more of the other blind units 16. Such a communication can be relayed via a single blind unit 16 if the blind unit is

within transmission range of both the reference unit 12 and the blind unit to be located 14. Such a communication path may be identified as a multi-hop communication path within a network where one or more intermediate units are needed to relay the communication, or more specifically a two-hop communication where only a single
5 intermediate unit is necessary.

In at least one embodiment of the present application, a nearby unit is generally included on a unit's neighbor list if the nearby unit is within communication range of the unit. Such a list can be maintained by keeping a list of the originator of recently received signals that are periodically broadcast by units within the network
10 and monitored by each of the other units.

FIG. 2 illustrates a more complete diagram of an overview of at least a portion of an exemplary communication network 30 illustrating the spatial relationship between members of a portion of the communication network 30. Similar to FIG. 1, the members are illustrated using triangles, squares, and circles. The triangles
15 similarly correspond to the location of reference units 32, the square similarly corresponds to a blind unit 34, which is the unit to be located, and the circle corresponds to the other nearby blind units 36, (only some of which have been associated with the corresponding reference number).

Similar to FIG. 1, each of the units have a corresponding communication
20 range. In FIG. 2, a communication range is illustrated for both the pair of reference units 32 and the unit to be located 34. In at least the illustrated embodiment, the communication range 38 is approximately the same for each of the units including the nearby blind units.

In the present invention, a unit determines its relative proximity to the nearby
25 reference units 32, based at least in part on the number of associated units 40, which are within communication range with the one or more nearby reference units 32. The closer a unit 34 is to a reference unit 32, the greater the likelihood that a larger number of associated blind units 40 will be nearby, which include the reference unit 32 in its neighbor list. In a two-hop system, where the associated units 40 are defined
30 as the units within communication range of the unit to be located 34, the number of associated units 40 which include a particular reference unit will be the units which

fall within a communication overlap region 42, which is larger when the unit to be located is closer to the reference unit. Generally, larger overlap regions have a greater chance that a larger number of other nearby blind units 36, will be contained in the overlap region 42.

5 The estimated location of the unit to be located 34, is then determined based upon a weighted average of the known location of the reference units, which are in communication range of either the unit to be located 34 or the other associated blind units 40. The weighting, in at least one instance, is based upon the total number of neighbor lists including the neighbor list of associated units 40 and the neighbor list of
10 the unit to be located 34, that include a particular reference unit 32. For example, in the illustrated embodiment, the reference unit 32A is present in five associated unit's neighbor lists, while reference unit 32B is present in three associated unit's neighbor lists.

 In at least one embodiment, the weighting is equal to the determined number
15 of neighbor list occurrences. In the illustrated embodiment this would result in an estimated location based upon the formulas:

$$X_{34} = (5X_{32A} + 3X_{32B}) / 8$$

$$Y_{34} = (5Y_{32A} + 3Y_{32B}) / 8$$

$$Z_{34} = (5Z_{32A} + 3Z_{32B}) / 8$$

20 wherein the variables X, Y and Z, correspond to the location of the identified units, for which the location of the reference units is presumed to be known.

 The formula could be expanded, as necessary, to take into account additional reference units, which may be present in the associated neighbor lists, and which would expand the number of terms and weighting values used in the numerator and
25 would also affect the sum of the weighting values, which in turn is used in the denominator when formulating the averages.

 While in the above noted example the weighting value used is directly equal to the number of relevant neighbor list occurrences, it is further possible that the weighting value could be determined based upon a formula, which takes into account
30 other features associated with each of the occurrences, or which further modifies the determined number of occurrences. For example the specific weighting value

associated with the averaging of each of the known reference locations could be based upon the square root of the number of occurrences in the relevant neighbor lists, or some other mathematical formula, which is historically determined to produce the desired results. The specific value could also be specifically tailored to accommodate
5 different methods of determining the associated units. For example, one such embodiment might count the number of occurrences of each reference unit that occurs in the neighbor lists of units, which are more than one hop away from the unit to be located 34.

Still further, the number of different occurrences in neighbor lists of associated
10 units may be counted at full or different fractional values dependent upon the number of hops the particular associated blind unit 40, corresponding to a particular neighbor list, is away from unit to be located 34.

Further yet, the formula for determining the weighting value based upon the number of occurrences in the associated neighbor lists could be adjusted based upon
15 the relationship between the average distance between the reference units 32 and the average communication range 38 of each of the units.

More generically, the formulas can be represented as:

$$\begin{aligned} X_{34} &= (W_{32A}X_{32A} + W_{32B}X_{32B} + \dots) / (W_{32A} + W_{32B} + \dots) \\ Y_{34} &= (W_{32A}Y_{32A} + W_{32B}Y_{32B} + \dots) / (W_{32A} + W_{32B} + \dots) \\ Z_{34} &= (W_{32A}Z_{32A} + W_{32B}Z_{32B} + \dots) / (W_{32A} + W_{32B} + \dots) \end{aligned}$$

20

where $X_{32\#}$, $Y_{32\#}$, $Z_{32\#}$ are the known coordinates of the corresponding reference units, and $W_{32\#}$ is the determined weighting.

In at least one embodiment, a set of reference units 52 are arranged in a predetermined pattern 50, which traverses an area within which it is desirable to be
25 able to locate a unit. One such example is illustrated in FIG. 3, where the reference units are generally equally spaced in both an east-to-west direction and a north-to-south direction, for purposes of estimating a location in at least two dimensions. In a further example, it may also be desirable to include similarly arranged layers spaced apart in an up-to-down direction, for purposes of assisting in the estimation of a
30 location in an additional third dimension. In these instances, the reference units are

spaced apart in two or more directions, which are generally orthogonal, relative to one another. FIG. 4 illustrates a still further possible predetermined pattern 54.

Generally, where the reference units 52 are associated with a predetermined pattern, the reference units 52 will often remain relatively stationary. In such an instance, the known or determined location value of each of the reference units could
5 be preprogrammed or hard-coded into at least some of the units. In some instances, the particular location value could be stored in each of the corresponding reference units and communicated to the nearby blind nodes, when the blind nodes determine their neighbor lists. Additionally and/or alternatively, each of the blind nodes could
10 include a master list of the location of each of the reference nodes.

In at least some embodiments, the reference units could be mobile. In some instances, the reference units, which are mobile, may be associated with a particular item whose location is similarly being tracked within the network. Because the reference units may be mobile, it may be necessary for these reference units to be able
15 to periodically determine their current location, which could be accomplished using an independent location determining device. One example of an independent location determining device could include a device which separately communicates with reference stations, located external to the network, such as one or more base transceiver stations and/or one or more global positioning satellites. The independent
20 location determining device could use different ranging techniques for purposes of triangulating their locations, such as time of arrival estimates, time difference of arrival estimates, and/or signal strength measurements, for communications between the reference units and the reference stations, when the reference units update their location.

Such an approach would allow a portion of the units to be tracked, which
25 include the generally more costly ranging circuitry, and in turn operate as reference units, which are then used in the determination of the other units, which would not necessarily include any ranging circuitry, using the above noted neighbor list location estimation technique. Where the reference units are mobile, and therefore
30 periodically needing to determine their location using an alternative location determining technique, a predetermined and prestored master location list present on

the blind nodes, may not be practical. In such an instance, the reference nodes current location could be communicated and stored, at the same time the neighbor list for each of the units is determined and compiled.

FIG. 5 illustrates a flow diagram of a method 100 for determining a location of a unit, in accordance with at least one aspect of the present invention. The method generally includes the unit to be located communicating 102 with the units within communication range. Neighbor lists are then established 104 for the unit to be located and each of a group of associated units. Reference units contained in each of the neighbor lists of the unit to be located and each of the associated units, are identified 106. An aggregate value of occurrences of each of the reference units in the corresponding neighbor lists is determined 108. Lastly, the location of the unit is determined 110 and/or estimated, based upon the aggregated value of the occurrences of the reference units in the corresponding neighbor lists.

As noted above, determining an aggregate value can be based upon counting the number of occurrences of each of the reference units in the neighbor list of the unit to be located and the neighbor list of each of the associated units, where in at least one embodiment the associated units includes the units in communication range of the unit to be located (i.e. 1-step away).

In at least one embodiment, a weighted average of the locations of the reference units identified in the corresponding neighbor lists is determined for purposes of estimating the location of the unit to be located.

FIG. 6 illustrates a block diagram of a location determination module 200 for use in a unit to be located 14, in accordance with at least one embodiment of the present invention. The location determination module 200 includes a transceiver 202 coupled to an antenna 204 for facilitating the wireless communication with other nearby units, and a processor 206 coupled to the transceiver 202. The processor 206 includes a storage area 208, which is adapted for storing data and/or sets of prestored instructions 210. At least some of the data takes the form of one or more neighbor lists 212, which are used to identify other units that are within communication range of the unit to be located 14. Additional data, which can be stored in the storage area may include one or more sets of predetermined locations associated with a set of

reference units 12 and/or current location values associated with the reference unit 12 received via communications with other nearby units.

The processor 206 further includes a discriminator 214, coupled to the storage area 208 for accessing the one or more stored neighbor lists 212, which is adapted for distinguishing between reference units and non-reference units contained in the one or more neighbor lists stored in the storage area 208. In at least one instance, a data bit could be set, which identifies the reference unit, or alternatively, all of the reference units may have an identification value, which falls within a predetermined range. One skilled in the art will appreciate that other techniques could alternatively be used, techniques which the discriminator 214 would be designed to detect.

The processor 206 additionally includes a calculation module 216, which determines the number of occurrences of each of the reference units 12 in the corresponding associated neighbor lists, and determines a location estimate for the unit to be located 14, based upon the determined number of occurrences and the known location of the corresponding reference units 12. In at least one embodiment, the discriminator and/or the calculation module can be implemented in the processor 206 as one or more sets of prestored instructions, stored in the storage area 208, and which are executed by the processor 206.

Generally, the location determination module 200 can be used in connection with the location of individual items and/or palettes of items in a warehouse environment, as suggested above. However, the location determination module 200 has additional applicability in other networks, wherein the determination of the location of individual elements is desired and a corresponding set of reference units and other non-reference units are available throughout the area to assist in determining a location estimate. At least one such example includes the location of devices such as one or more cellular telephones or other wireless communication devices located within a network.

Still further, the location determination module could be incorporated as part of the equipment for one or more groups of personnel operating in concert within a given area or environment. One such example includes emergency personnel. In this

instance the location determination module could be located in one or more of a fire fighter's helmet, jacket, or other piece of equipment.

Further yet, the location determination module could be made to function with many different forms of wireless communications including communications using a cellular telephone radio transceiver, a cordless telephone radio transceiver, a wireless LAN connection, a short range radio transceiver, such as a Bluetooth transceiver, an infra-red communication transceiver, or other similar communication device not constrained by a physical wired connection. Still further the location module could interact with an installed sprinkler system, which might include wireless transceivers, which function as reference units.

FIG. 7 illustrates a block diagram of a reference unit 300 for use in determining a location estimate of the unit to be located, in accordance with at least one embodiment of the present invention. The reference unit 300 includes a transceiver 302 and corresponding antenna 304. In at least some embodiments, the transceiver 302 has at least one operating mode, in which the communication range is substantially similar to the transmission range of a corresponding operating mode associated with the location determination module 200. The reference unit additionally includes a processor 306, coupled to the transceiver 302, which manages the overall operation of the reference unit 300.

In some instances, the processor 306 of the reference unit 300 will maintain, store and communicate, as needed, a neighbor list 308. The processor 306, in at least some of the same or other instances, may also include a reference unit location 310, which can be either determined, periodically or as needed, or can be previously determined, depending upon the operational characteristics of the unit. Where the unit is allowed to change location (i.e. the unit is not substantially fixed in place), the use of a predetermined previously stored location may be problematic, if the unit does not have an ability to determine and/or update its new location. At least some embodiments, may include an alternate location determining device 312, which can communicate with one or more reference stations, which may be external to the networks, such as one or more base transceiver station 314 and/or one or more global positioning satellites 316.

Generally, the alternate location determining device 312 has a greater transmission range, which enables it to communicate with reference stations located beyond the bounds of the network. In some instances, this may be accomplished via a separate transceiver coupled to a separate antenna 318. In other instances, this may be accomplished by temporarily increasing the transmission power in conjunction with at least a second operating mode of transceiver 302, coupled to antenna 304. In at least some instances, the alternate location determining device 312 will include circuitry for determining range information relative to the reference stations. The range information can then be used by the reference unit 300, in conjunction with the known or determined location of the reference stations, in order to triangulate the position of the reference unit 300. In turn, the determined location of the reference units 300 are used by the blind units 14 to estimate the location of one or more blind units to be located 14, as noted above.

In this way, a network environment is described, which includes units to be located, which can estimate their location, without the use of range determining circuitry, based upon the neighbor lists of the unit to be located 14 and neighbor lists of associated units and the corresponding number of occurrences of the reference units within the respective neighbor lists, and based upon the known location of the reference units.

While the preferred embodiments of the invention have been illustrated and described, it is to be understood that the invention is not so limited. Numerous modifications, changes, variations, substitutions and equivalents will occur to those skilled in the art without departing from the spirit and scope of the present invention as defined by the appended claims.